US009450311B2

(12) **United States Patent**
Ng et al.

(10) **Patent No.: US 9,450,311 B2**
(45) **Date of Patent: Sep. 20, 2016**

(54) **POLARIZATION DEPENDENT ELECTROMAGNETIC BANDGAP ANTENNA AND RELATED METHODS**

(71) Applicant: **Raytheon Company**, Waltham, MA (US)

(72) Inventors: **Jackson Ng**, Tucson, AZ (US); **Charles G. Gilbert**, Tucson, AZ (US)

(73) Assignee: **Raytheon Company**, Waltham, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 378 days.

(21) Appl. No.: **13/949,505**

(22) Filed: **Jul. 24, 2013**

(65) **Prior Publication Data**

US 2015/0029062 A1 Jan. 29, 2015

(51) **Int. Cl.**

H01Q 1/38	(2006.01)
H01Q 15/24	(2006.01)
H01Q 1/27	(2006.01)
H01Q 1/28	(2006.01)
H01Q 1/48	(2006.01)
H01Q 9/30	(2006.01)
H01Q 15/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H01Q 15/24*** (2013.01); ***H01Q 1/27*** (2013.01); ***H01Q 1/286*** (2013.01); ***H01Q 1/48*** (2013.01); ***H01Q 9/30*** (2013.01); ***H01Q 15/008*** (2013.01)

(58) **Field of Classification Search**

CPC H01Q 1/38; H01Q 9/16; H01Q 15/02
USPC .... 343/700 MS, 729, 795, 909
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,287,518	A *	9/1981	Frosch	H01Q 9/065 343/700 MS
5,892,485	A *	4/1999	Glabe	H01Q 19/108 343/756
6,441,792	B1	8/2002	Sievenpiper et al.	
6,952,184	B2	10/2005	Sievenpiper et al.	
7,855,689	B2	12/2010	Fukui et al.	

(Continued)

FOREIGN PATENT DOCUMENTS

WO	WO 01/69724 A1	9/2001
WO	WO 02/103846 A1	12/2002

OTHER PUBLICATIONS

PCT Search Report of the ISA for PCT/US2014/038317 dated Aug. 8, 2014 5 pages.

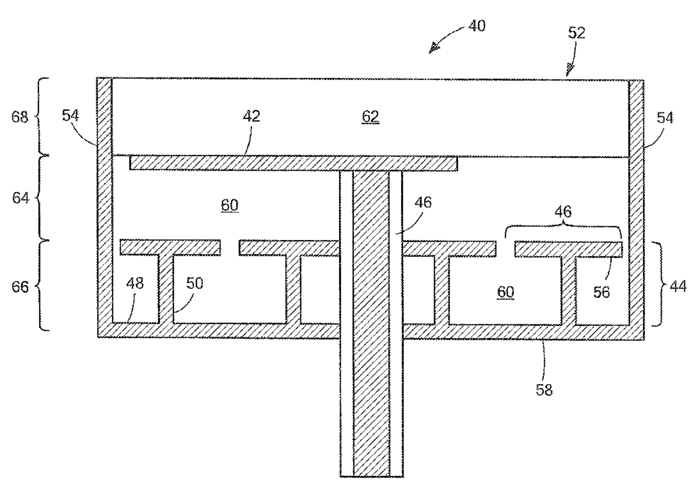
(Continued)

Primary Examiner — Dameon E Levi
Assistant Examiner — Collin Dawkins
(74) *Attorney, Agent, or Firm* — Daly, Crowley, Mofford and Durkee, LLP

(57) **ABSTRACT**

A rotationally polarized antenna includes a radiating element that is held in a skewed orientation with respect to an underlying polarization-dependent electromagnetic band gap (PDEBG) structure. The radiating element and the PDEBG structure are both housed within a conductive cavity. The radiating element, the PDEBG structure, and the cavity are designed together to achieve an antenna having improved operational characteristics (e.g., an enhanced circular polarization bandwidth, etc.). In some embodiments, the antenna may be implemented as a flush mounted or conformal antenna on an outer surface of a supporting platform.

29 Claims, 11 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

8,188,928	B2	5/2012	Lin et al.	
2005/0068233	A1*	3/2005	Tanaka	H01Q 9/42 343/700 MS
2009/0002240	A1*	1/2009	Sievenpiper	H01Q 15/0013 343/700 MS

OTHER PUBLICATIONS

PCT Written Opinion of the ISA for PCT/US2014/038317 dated Aug. 8, 2014 6 pages.

Best, et al.; "Electromagnetic Band Gap (EBG) Surfaces for Antenna Applications;" MITRE Innovation Exchange; Presentation; Jan. 2008; 9 pages.

Kim, et al.; "Reflecting Characteristics of 1-D EBG Ground Plane and It's Application to a Planar Dipole Antenna;" Progress in Electromagnetics Research; vol. 1; Aug. 2011; pp. 51-66.

Office Action dated Jan. 30, 2014, U.S. Appl. No. 13/457,546, filed Apr. 27, 2012, pp. 1-20.

Office Action dated Jan. 30, 2014, U.S. Appl. No. 13/457,547, filed Apr. 27, 2012, pp. 1-22.

* cited by examiner

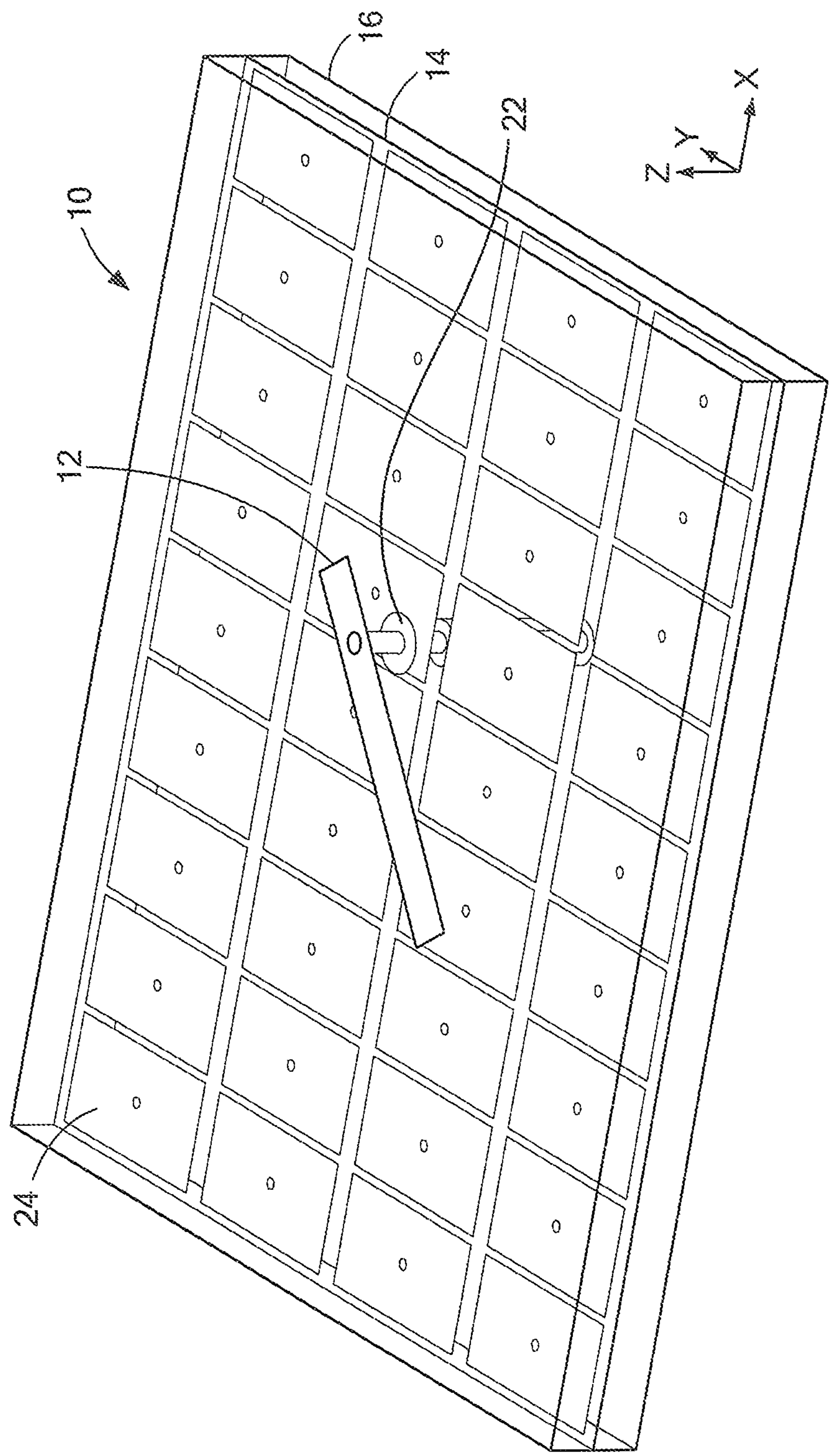


FIG. 1

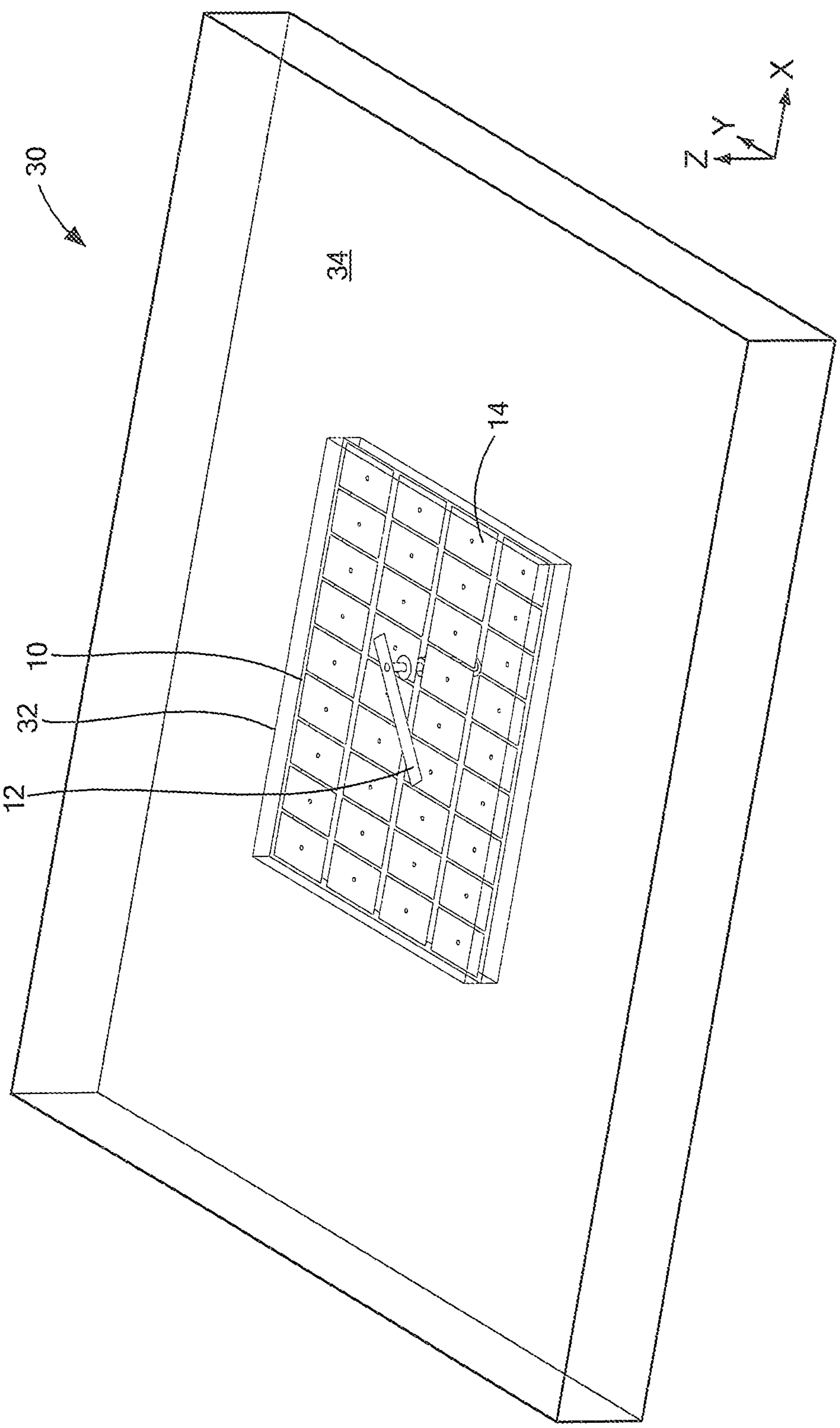


FIG. 2

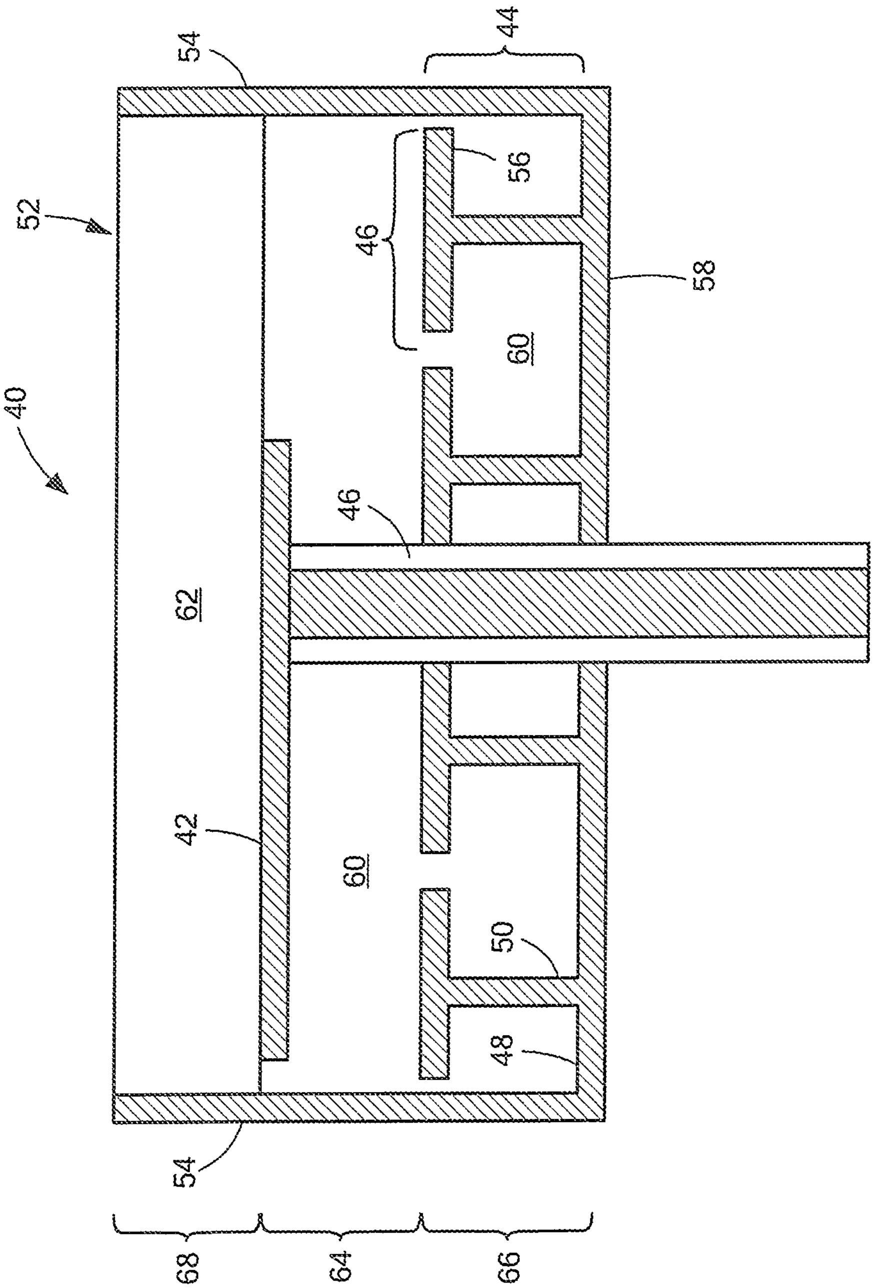


FIG. 3

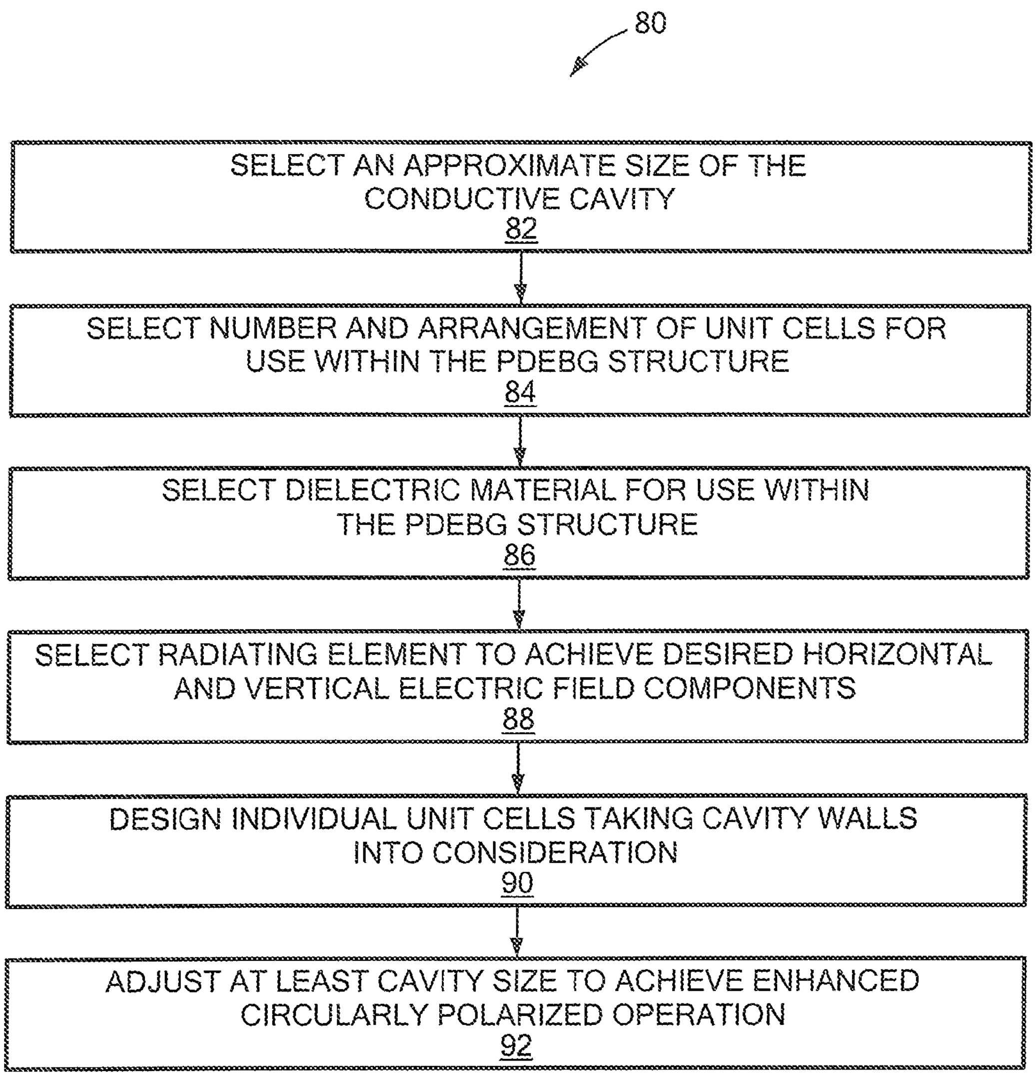

80
SELECT AN APPROXIMATE SIZE OF THE CONDUCTIVE CAVITY
82
SELECT NUMBER AND ARRANGEMENT OF UNIT CELLS FOR USE WITHIN THE PDEBG STRUCTURE
84
SELECT DIELECTRIC MATERIAL FOR USE WITHIN THE PDEBG STRUCTURE
86
SELECT RADIATING ELEMENT TO ACHIEVE DESIRED HORIZONTAL AND VERTICAL ELECTRIC FIELD COMPONENTS
88
DESIGN INDIVIDUAL UNIT CELLS TAKING CAVITY WALLS INTO CONSIDERATION
90
ADJUST AT LEAST CAVITY SIZE TO ACHIEVE ENHANCED CIRCULARLY POLARIZED OPERATION
92

FIG. 4

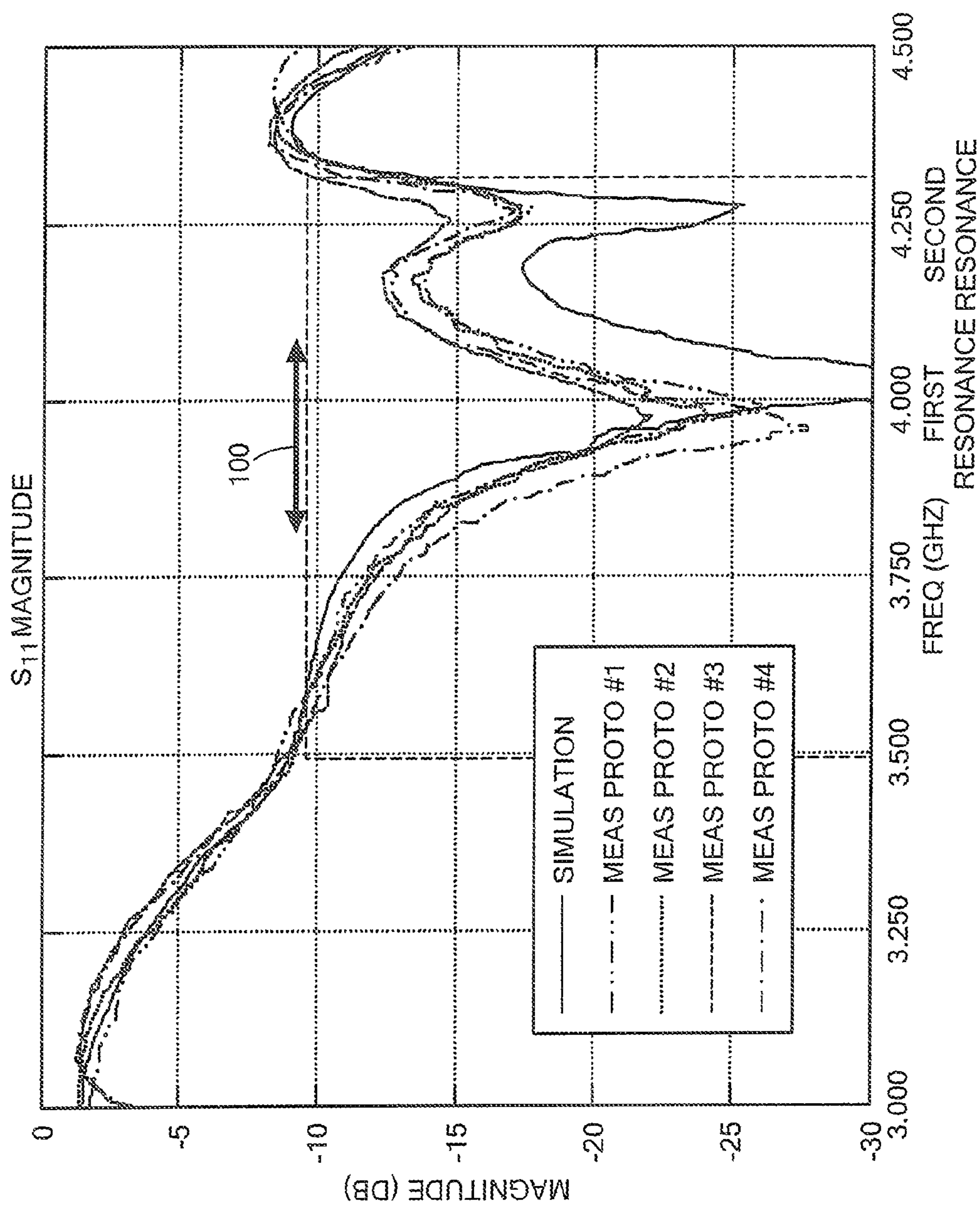
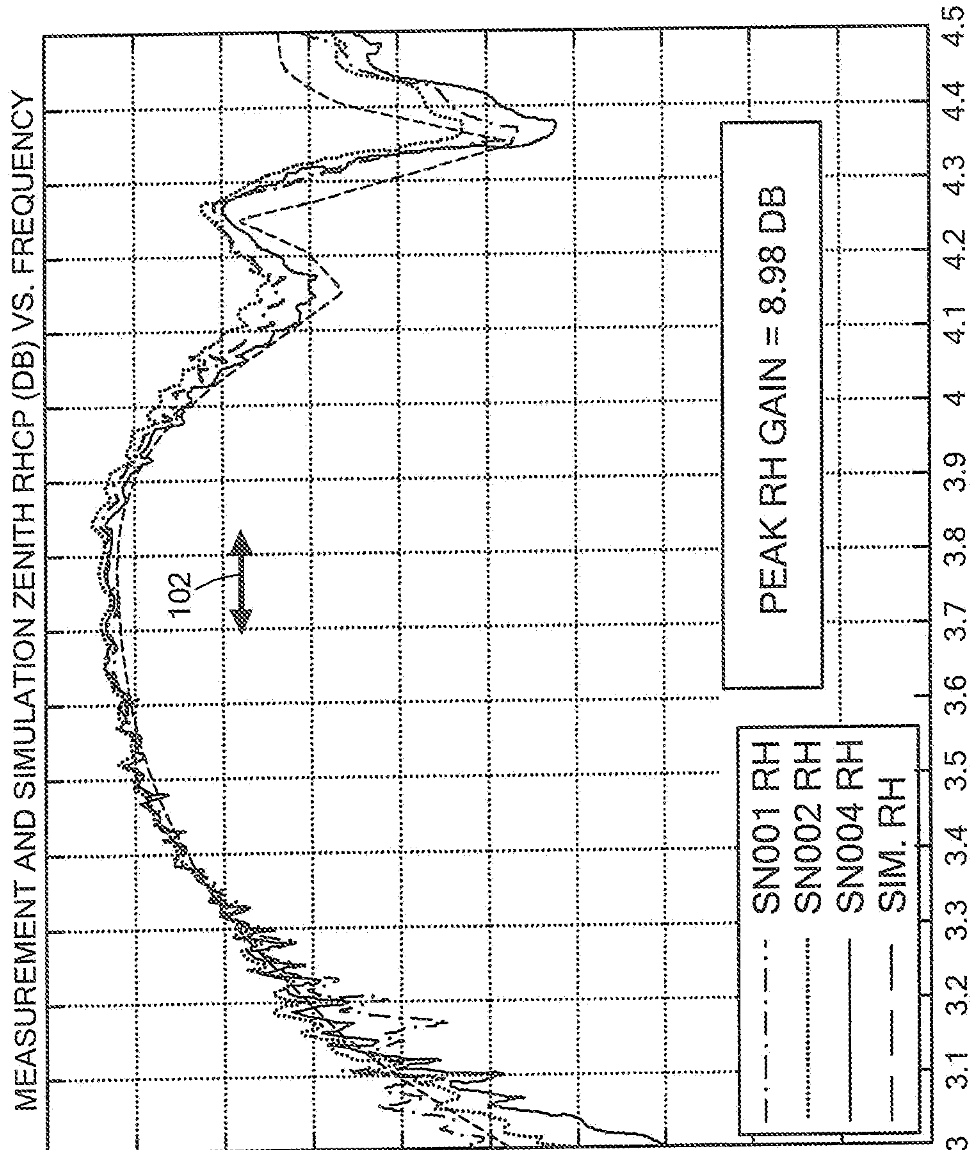

S_{11} MAGNITUDE
MAGNITUDE (DB)
0
-5
-10
-15
-20
-25
-30
3.000
3.250
3.500
3.750
4.000
4.250
4.500
FREQ (GHZ)
FIRST RESONANCE
SECOND RESONANCE
100
SIMULATION
MEAS PROTO #1
MEAS PROTO #2
MEAS PROTO #3
MEAS PROTO #4

FIG. 5



MEASUREMENT AND SIMULATION ZENITH RHCP (DB) VS. FREQUENCY
ZENITH RHCP (DB)
10
8
6
4
2
0
-2
-4
-6
-8
-10
FREQUENCY (GHZ)
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
102
PEAK RH GAIN = 8.98 DB
SN001 RH
SN002 RH
SN004 RH
SIM. RH

FIG. 6

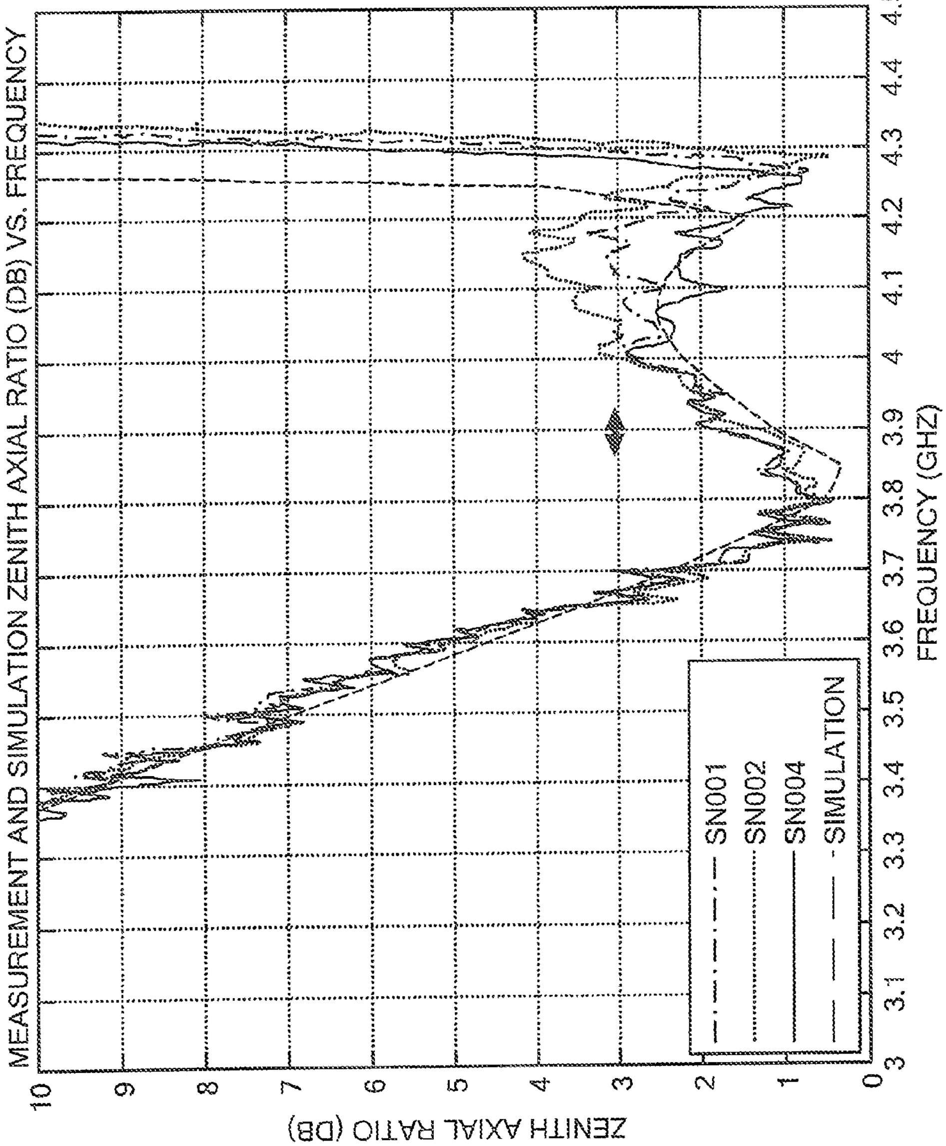

MEASUREMENT AND SIMULATION ZENITH AXIAL RATIO (DB) VS. FREQUENCY
ZENITH AXIAL RATIO (DB)
10
9
8
7
6
5
4
3
2
1
0
FREQUENCY (GHZ)
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
SN001
SN002
SN004
SIMULATION

FIG. 7

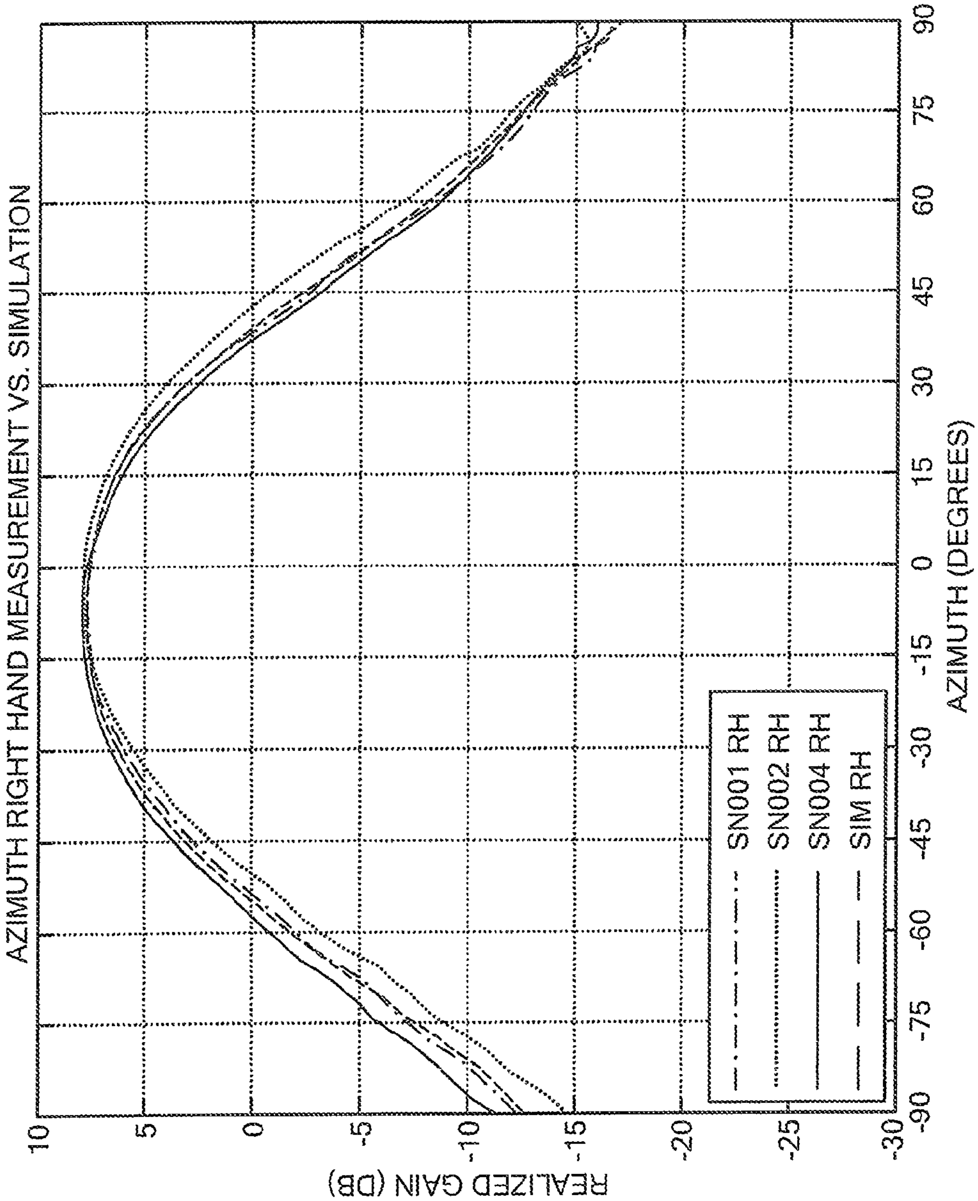

AZIMUTH RIGHT HAND MEASUREMENT VS. SIMULATION
REALIZED GAIN (DB)
10
5
0
-5
-10
-15
-20
-25
-30
-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90
AZIMUTH (DEGREES)
SN001 RH
SN002 RH
SN004 RH
SIM RH

FIG. 8

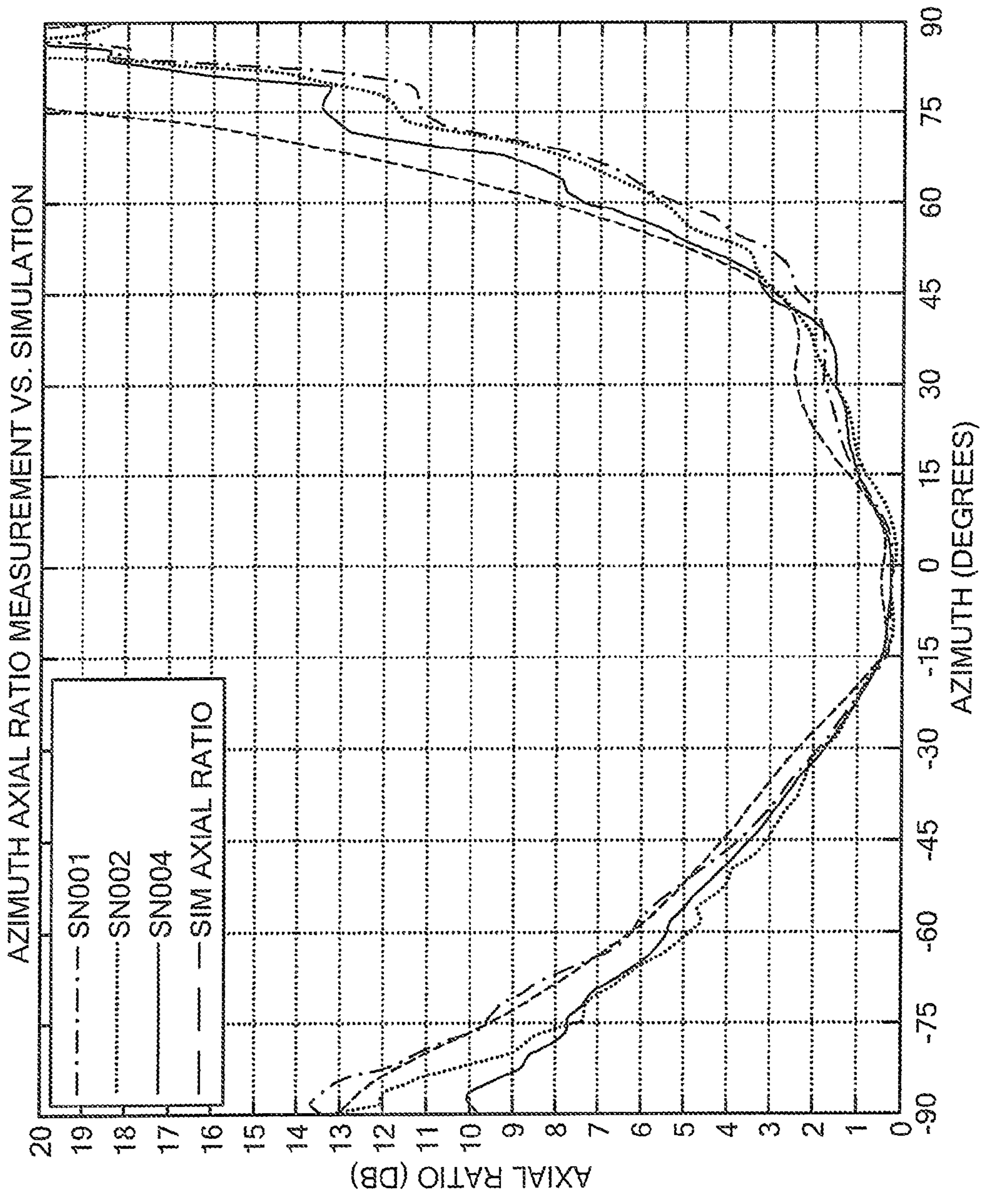

AZIMUTH AXIAL RATIO MEASUREMENT VS. SIMULATION
SN001
SN002
SN004
SIM AXIAL RATIO
AXIAL RATIO (DB)
AZIMUTH (DEGREES)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
-90
-75
-60
-45
-30
-15
0
15
30
45
60
75
90

FIG. 9

ANTENNA TYPE	FREQ (GHZ)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	VSWR 2:1 BW	AR 6 DB	AR 3 DB	MAX ZENITH CP GAIN (DB)
EM COUPLED CP	2.2	3	2.41	0.24	8.40%	3.50%	1.30%	5.65
		0.56Λ	0.45Λ	0.045Λ				
EBG CP	3.84	2.677	2.52	0.302	20.72%	19.08%	15.58%	8.98
		0.79Λ	0.75Λ	0.09Λ				

FIG. 10

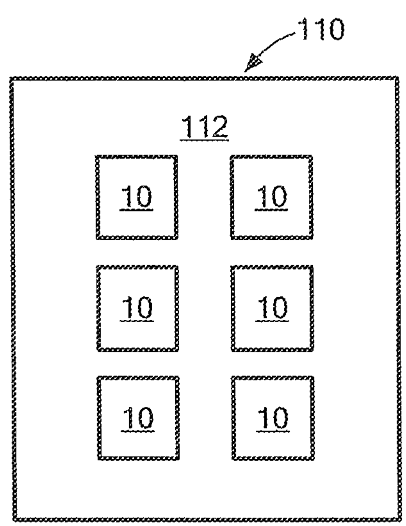


FIG. 11

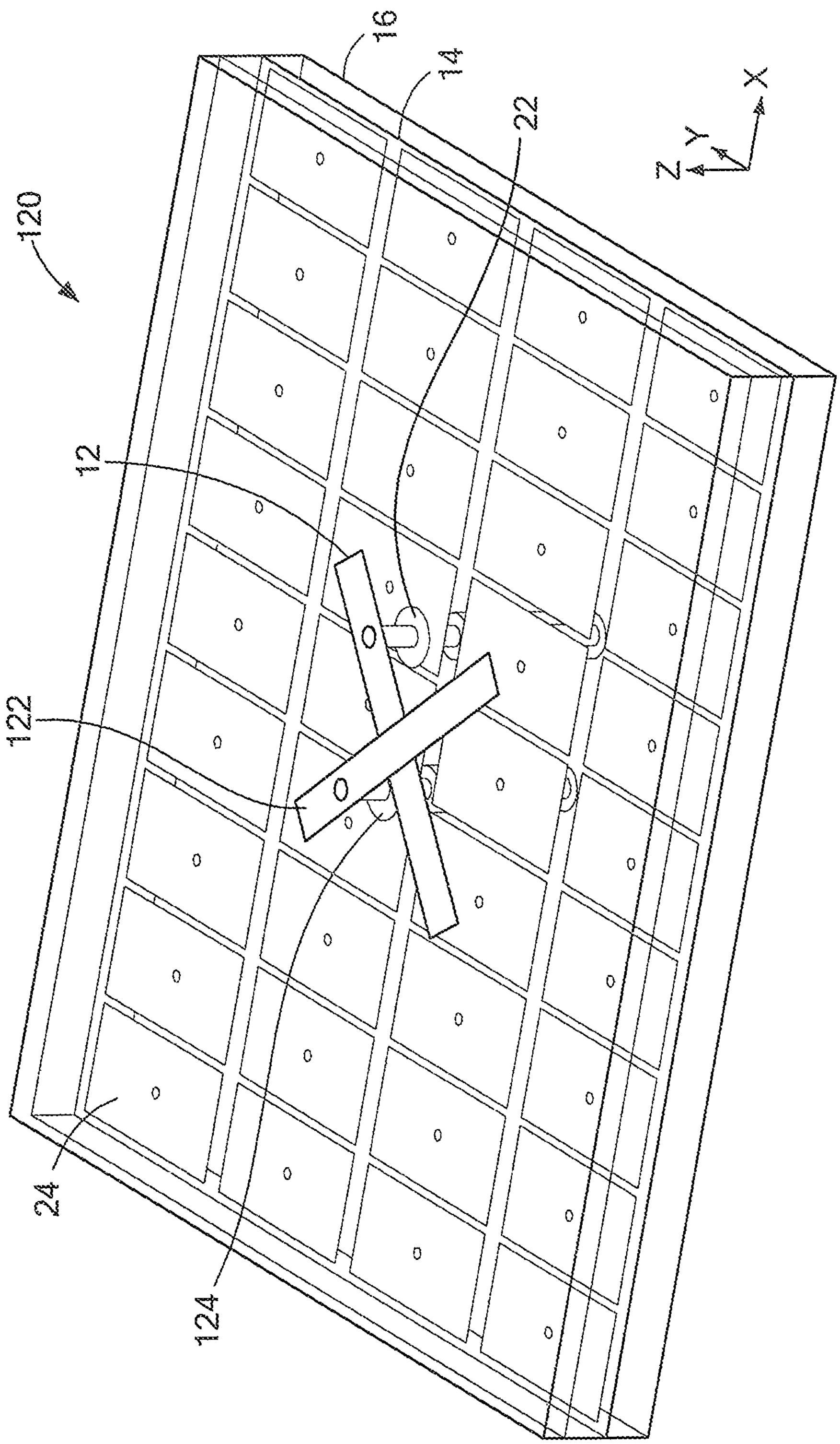


FIG. 12

POLARIZATION DEPENDENT ELECTROMAGNETIC BANDGAP ANTENNA AND RELATED METHODS

BACKGROUND

To establish a communications link, many systems (e.g., telemetry systems, Aegis, many RMS products, etc.) require antennas having high bandwidth and high gain that can be mounted flush with the skin of a missile, aircraft, or other platform, and packaged in a limited volume. Circular polarized antennas may be needed to establish a communications link when the flight orientation of a platform cannot be maintained. Higher bandwidths and higher gains are often needed to satisfy ever increasing requirements for communication distance and data rate. Flush mounted antennas minimize aerodynamic effects for an underlying platform. A volume-limited antenna can reduce or minimize mass impact. There is a need for antenna designs that are capable of achieving any combination of the above-described qualities or all of these qualities.

SUMMARY

In accordance with one aspect of the concepts, systems, circuits, and techniques described herein, a rotationally polarized antenna comprises: a ground plane; a polarization dependent electromagnetic band gap (PDEBG) structure disposed above the ground plane, the PDEBG structure having a number of unit cells arranged in rows and columns; a radiating element disposed above the PDEBG structure, the radiating element having a long dimension and a short dimension; and a conductive cavity encompassing the PDEBG structure and the radiating element, the conductive cavity being open on a radiating side of the antenna; wherein the radiating element is oriented at a non-zero angle with respect to the rows and columns of the PDEBG structure.

In one embodiment, the antenna is configured for use with circularly polarized waves.

In one embodiment, the PDEBG structure, the radiating element, and the conductive cavity are configured together to achieve an enhanced operational bandwidth.

In one embodiment, the radiating element is oriented at an angle with respect to the rows and columns of the PDEBG structure that supports substantially equal horizontal and vertical electric field magnitudes for use with circularly polarized waves.

In one embodiment, the radiating element is oriented at an angle with respect to the rows and columns of the PDEBG structure that supports different horizontal and vertical electric field magnitudes for use with non-circular elliptically polarized waves.

In one embodiment, a distance between side walls of the conductive cavity and the outermost edges of the PDEBG structure is configured to produce an additional resonance in an electrical response of the antenna that enhances a bandwidth thereof.

In one embodiment, the radiating element includes one of: a patch element, a dipole element, and a monopole element.

In one embodiment, the antenna further comprises a feed coupled to the radiating element through the ground plane and the PDEBG structure.

In one embodiment, the conductive cavity has a floor that serves as the ground plane of the antenna.

In one embodiment, the antenna further comprises a radome layer covering an upper surface of the radiating element.

In one embodiment, an upper surface of the radome layer is substantially flush with an upper edge of the conductive cavity.

In one embodiment, an upper surface of the radiating element is substantially flush with an upper edge of the conductive cavity.

In one embodiment, the conductive cavity is formed within an outer skin of a vehicle; and an upper surface of the antenna is flush with the outer skin of the vehicle.

In one embodiment, the vehicle includes one of: a ground vehicle, a watercraft, an aircraft, and a spacecraft.

In one embodiment, a length, a width, and a height of the conductive cavity are each less than a wavelength at the center frequency of the antenna.

In one embodiment, the antenna is conformal to a curved surface of a mounting platform.

In one embodiment, the radiating element is a first radiating element; and the antenna further comprises a second radiating element disposed above the PDEBG structure, the second radiating element having a long dimension and a short dimension, the second radiating element having an orientation that is orthogonal to an orientation of the first radiating element, wherein the second radiating element is on a different metal layer than the first radiating element.

In accordance with another aspect of the concepts, systems, circuits, and techniques described herein, an antenna assembly for use in forming a rotationally polarized antenna, comprises: a polarization dependent electromagnetic band gap (PDEBG) structure having a plurality of unit cells arranged in rows and columns; and a radiating element disposed above the PDEBG structure, the radiating element having a long dimension and a short dimension, the radiating element being held in a fixed position with respect to the PDEBG structure so that the long dimension of the radiating element firms a non-zero angle with both the rows and columns of the PDEBG structure; therein the antenna assembly is configured for insertion into a conductive cavity having dimensions that are selected to form an antenna having radiation performance that is characteristic of a larger antenna.

In one embodiment, the PDEBG structure and the radiating element are formed on printed circuit boards.

In one embodiment, the antenna assembly further comprises a ground plane on an opposite side of the PDEBG structure from the radiating element, the ground plane to contact a floor of the conductive cavity when the antenna assembly is installed therein.

In one embodiment, the PDEBG structure is sized and positioned to form predetermined capacitances with walls of the conductive cavity when the antenna assembly is installed therein to form at least one additional resonance in an electrical response of the antenna that increases a bandwidth of the response above what it would be without the conductive cavity.

In one embodiment, the antenna assembly farther comprises a feed coupled to the radiating element through the PDEBG structure.

In one embodiment, the radiating element is a patch element.

In one embodiment, the radiating element is one of: a dipole element and a monopole element.

In one embodiment, the radiating element is oriented at an angle with respect to the rows and columns of the PDEBG structure that supports substantially equal horizontal and vertical electric field components for use with circularly polarized waves.

In one embodiment, the radiating element is oriented at an angle with respect to the rows and columns of the PDEBG structure that supports different horizontal and vertical electric field magnitudes for use with elliptically polarized waves.

In one embodiment, the antenna assembly is designed for insertion into a conductive cavity within an outer skin of a vehicle; and the antenna assembly has a height that allows the antenna assembly to be mounted in the conductive cavity substantially flush to the outer skin of the vehicle.

In one embodiment, the radiating element is a first radiating element; and the antenna assembly further comprises a second radiating element disposed above the PDEBG structure, the second radiating element having a long dimension and a short dimension, the second radiating element having an orientation that is orthogonal to an orientation of the first radiating element, wherein the second radiating element is on a different metal layer than the first radiating element.

In accordance with a still another aspect of the concepts, systems, circuits, and techniques described herein, a method is provided for designing a rotationally polarized antenna having a radiating element disposed above a polarization-dependent electromagnetic band gap (PDEBG) structure within a conductive cavity, the radiating element being oriented at a non-zero angle with respect to the PDEBG structure. More specifically, the method comprises: determining an approximate size of the conductive cavity; selecting a dielectric material and a number and arrangement of unit cells to use in the PDEBG structure that will fit within the approximate size of the conductive cavity; selecting a radiating element; designing a unit cell of the PDEBG structure that will result in a 90 degree phase shift between total horizontal and vertical electric field components of the antenna, wherein designing a unit cell takes into consideration performance effects of the conductive cavity on the operation of the PDEBG structure; and adjusting a size of at least the conductive cavity to achieve an enhanced bandwidth for the rotationally polarized antenna.

In one embodiment, designing a unit cell of the PDEBG structure includes using electromagnetic simulation software.

In one embodiment, designing a unit cell of the PDEBG structure includes modeling a capacitance between walls of the conductive cavity and edges of the PDEBG structure.

In one embodiment, the method further comprises selecting a second radiating element to be mounted above the PDEBG structure and the first radiating element, the second radiating element to be oriented in a direction that is orthogonal to an orientation direction of the first radiating element.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features may be more fully understood from the following description of the drawings in which:

FIG. **1** is a projection view illustrating an exemplary antenna assembly in accordance with an embodiment;

FIG. **2** is a projection view illustrating an exemplary antenna having the antenna assembly of FIG. **1** mounted within a conductive cavity in accordance with an embodiment;

FIG. **3** is a sectional side view of an exemplary antenna in accordance with an embodiment;

FIG. **4** is a flowchart illustrating an exemplary method for designing an antenna in accordance with an embodiment;

FIG. **5** is a plot illustrating an input impedance response of an exemplary antenna design in accordance with an embodiment;

FIG. **6** is a plot illustrating antenna gain at zenith for right hand circular polarization (RHCP) operation versus frequency for the exemplary antenna design;

FIG. **7** is a plot illustrating axial ratio (AR) at zenith versus frequency for the exemplary antenna design;

FIG. **8** is a plot illustrating gain versus azimuth angle for right hand circular polarization (RHCP) operation for the exemplary antenna design;

FIG. **9** is a plot illustrating axial ratio (AR) versus azimuth angle for the exemplary antenna design;

FIG. **10** is a table comparing operational parameters of the exemplary antenna design to those of a prior EM coupled, circularly polarized antenna design;

FIG. **11** is a front view illustrating an exemplary array antenna in accordance with an embodiment; and

FIG. **12** is a projection view illustrating an exemplary antenna assembly having two radiating elements in accordance with an embodiment.

DETAILED DESCRIPTION

The subject matter described herein relates to antenna designs that are capable of providing high gain and wide circular polarization (or elliptical polarization) bandwidth from a relatively small, low profile package. The antenna designs are particularly well suited for use in antenna applications requiring flush mounting (e.g., airborne applications, conformal arrays, etc). The antenna designs are also well suited for use in other applications where small antenna size is desired, such as hand held wireless communicators and wireless networking products. In some implementations, the antenna designs may be used to provide RMS antennas, although many other applications exist. Conventional low profile, limited volume, circularly-polarized antenna designs have suffered from narrow impedance bandwidth and narrow circular polarization bandwidths. For example, the typical 3 dB axial ratio bandwidth in such antennas is less than 2%. In at least one embodiment described herein, 3 dB axial ratio bandwidths of up to 15.58% have been achieved, with impedance bandwidths of up to 20.72%, in antenna systems that provide high gain, conformal mounting, and limited volume.

Although described in the context of circular polarization in various places herein, it should be appreciated that the techniques and structures described herein may also be used to support non-circular, elliptically polarized operation in some embodiments. As used herein, the terms "rotational polarization," "rotationally polarized," and the like are used to describe propagating waves having rotating electric field polarizations, such as elliptically polarized and circularly polarized waves, and structures for use therewith.

In various embodiments described herein, antennas are provided that include a radiating element held in a fixed orientation relative to a polarization-dependent electromagnetic band gap (PDEBG) structure, with both the radiating element and the PDEBG structure mounted within a conductive cavity. To support circular polarization, the radiating element may be oriented at a non-zero angle with respect to the PDEBG structure so that the total radiating fields of the antenna have substantially equal magnitude for x-polarization and y-polarization. To support non-circular elliptical polarization, the radiating element may be oriented at an angle that results in total radiating fields of the antenna that have unequal magnitude for x-polarization and y-polarization. For both circular and elliptical polarization, the PDEBG structure can be designed to achieve total radiating fields with 90° phase difference between x-polarization and y-polarization. As will be described in greater detail, the conductive cavity allows the antenna to be flush-mounted if desired and, with proper design, also permits an increase in rotationally polarized bandwidth to be achieved.

Electromagnetic band gap (EBG) structures are periodic structures that exhibit interesting qualities in the presence of electromagnetic waves. A polarization-dependent electromagnetic band gap (PDEBG) structure is an EBG structure that has response characteristics that depends upon the polarization of an incident electromagnetic wave. That is, the PDEBG will respond differently to a horizontally polarized wave at a particular frequency than it will to a vertically polarized wave at the same frequency. One property of EBG structures that has proven very useful in the field of antennas is the ability to, at least in part, act as a magnetic conductor surface. As is well known, an electromagnetic wave incident upon a perfect electric conductor surface will be reflected with a phase change of 180 degrees. Conversely, an electromagnetic wave incident upon a perfect magnetic conductor surface, if such a thing could exist, would be reflected with a phase change of zero degrees. EBG structures can be designed that reflect electromagnetic waves at desired angles between zero and 180 degrees. In addition, it is also possible to design EBG structures that reflect electromagnetic waves having a first polarization direction (e.g., horizontal) at one phase angle and electromagnetic waves having a second polarization direction (e.g., vertical) at a different phase angle. As will be described in greater detail, these properties can be taken advantage of by an antenna designer to achieve an antenna capable of circularly polarized operation.

In the discussion that follows, a right-hand Cartesian coordinate system (CCS) will be assumed when describing the various antenna structures. To simplify description, the direction normal to the face of an antenna will be used as the z-direction of the CCS (with unit vector z), the direction along a longer side of the antenna will be used as the x-direction (with unit vector x), and the direction along a shorter side of the antenna will be used as the y direction (with unit vector y). It should be appreciated that the structures illustrated in the various figures disclosed herein are not necessarily to scale. That is, one or more dimensions in the figures may be exaggerated to, for example, increase clarity and facilitate understanding.

FIG. **1** is a projection view illustrating an exemplary antenna assembly **10** in accordance with an embodiment. As will be described in greater detail, the antenna assembly **10** may be installed within a conductive cavity to form as completed antenna. As illustrated, the antenna assembly **10** includes a radiating element **12** mounted above a polarization-dependent electromagnetic band gap (PDEBG) structure **14**. A ground plane **16** may be provided below the PDEBG structure **14**. The PDEBG structure **14** may include a plurality of units cells **24** that are arranged in a periodic fashion (e.g., equally spaced rows and columns). The size, shape, and proximity of the various unit cells **24** will, to a large extent, dictate the operational properties of the PDEBG structure **14**. A feed **22** may be provided to feed the radiating element **12**. In the illustrated embodiment, the feed **22** is a coaxial feed that extends through the PDEBG structure **14** and the ground plane **16** from below. Other techniques for feeding the radiating element **12** may alternatively be used. To facilitate operation with circularly-polarized signals, as will be described in greater detail, the radiating element **12** may be oriented at a non-zero angle with respect to the units cells **24** of the PDEBG structure **14** (i.e., at a non-zero angle with respect to the x and y axes in FIG. **1**).

FIG. **2** is a projection view showing the antenna assembly **10** of FIG. **1** mounted within a conductive cavity **32** to form an antenna **30** in accordance with an embodiment. In some implementations, the antenna assembly **10** may be mounted within the conductive cavity **32** so that an outermost surface of the antenna assembly **10** is flush with a surface **34** associated with the conductive cavity **32** (e.g., a conductive surface within which the cavity **32** is formed). As is well known, flush mounting may be desired to reduce the aerodynamic impact of the antenna **30** in certain applications. The antennas and techniques described herein are not limited to use in flush mounted applications, however. In some embodiments, the conductive cavity **32** may include, for example, a depression within an outer conductive skin **34** of a vehicle (e.g., ground vehicle, an aircraft, a missile, a spacecraft, a watercraft, etc.).

The antenna assembly **10** may be fixed within the conductive cavity **32** in any known manner including using, for example, an adhesive, solder, a compression fit, clamps, or any other technique that is capable of securing the assembly **10** in place. In some embodiments, instead of first forming the antenna assembly **10** and then mounting it within the cavity **32**, the PDEBG structure **14** and the radiating element **12** may be assembled within the conductive cavity **32**. In the illustrated embodiment, an elongated patch radiating element **12** is used in the antenna **30**. It should be appreciated, however, that any type of element may be used that can operate as a linear electric field source.

With reference to FIG. **2**, to support circularly-polarized operation, the PDEBG structure **14** may be designed so that the reflection phase of the structure is dependent on the polarization of an incident wave. Thus, a horizontally polarized electromagnetic wave will be reflected by the PDEBG structure **14** with a first phase angle and a vertically polarized wave will be reflected with a second phase angle that is different from the first phase angle. The radiating element **12** is mounted at a non-zero angle with respect to the x and y axes so that a transmitted signal has both a horizontal and a vertical electric field component. Portions of the transmitted signal will travel backwards (i.e., in the −z direction) from the radiating element **12** and be reflected from the PDEBG structure **14**. The horizontal and vertical components of the signal will be reflected at different phases. The antenna **30** may be designed so that the difference between the overall horizontal electric field component and the overall vertical electric field component emitted from the antenna will be (nominally) 90 degrees out of phase within a frequency range of interest. As is well known, a circularly polarized signal requires the combination of two orthogonally polarized signals that are 90 out of phase with one another. To support circularly-polarized operation, the orientation of the radiating element **12** with respect to the x and y axes may be selected to achieve a substantially equal electric field magnitude in the horizontal and vertical electric field components. To support elliptically-polarized operation (non-circular), the orientation of the radiating element **12** with respect to the x and y axes may be selected to achieve different electric field magnitudes in the horizontal and vertical directions.

FIG. **3** is a sectional side view of an antenna **40** in accordance with an embodiment. As shown, the antenna **40** includes a radiating element **42** disposed above a PDEBG structure **44**, within a conductive cavity **52**. The PDEBG structure **44** includes a plurality of unit cells **46** situated above a ground plane **48**. Each unit cell **46** includes a horizontal, conductive EBG element **56** that is conductively coupled to the ground plane **48** by a conductive connection **50**. In the illustrated embodiment, the PDEBG structure **44** is a particular form of EBG structure known as a mushroom EBG. It should be understood that other types of EBG structures that support circular polarized waves may be used in other embodiments. A coaxial feed **46** is provided to feed the radiating element **42** from below. As shown, the coaxial feed **46** extends through the ground plane **48** and the PDEBG structure **44**.

The conductive cavity **52** of FIG. **3** includes wall portions **54** and a floor portion **58**. The wall portions **54** may surround the radiating element **42** and the PDEBG structure **44** on all sides. The antenna **40** will transmit and/or receive electromagnetic signals through a top of the cavity **52** which remains open. In some embodiments, the floor portion **58** of the conductive cavity **52** may serve as the ground plane **48** of the antenna. In other embodiments, a separate ground plane **48** may be provided. Dielectric material **60** may fill the gaps between the conductive elements of the antenna **40**. A dielectric radome **62** may be provided above the radiating element **42** to, among other things, protect the radiating element **42** and other circuitry from an exterior environment. In some implementations, an upper surface of the radome **62** may be flush with an upper edge of the cavity **52** (although this is not required).

The antenna designs of FIGS. **1**, **2**, and **3** may be built in any of a variety of ways. In some embodiments, these designs may be formed using relatively simple and well known printed circuit board (PCB) techniques. Thus, with reference to FIG. **3**, radiating element **42** may include a metallic trace patterned on an upper surface of as first dielectric board **64** and the conductive elements **56** of the PDEBG structure **44** may include metallic traces patterned on an upper surface of a second dielectric board **66**. The ground plane **48** may include a metallization layer on a lower surface of the second dielectric board **66**. The conductive connections **50** may be formed using via connections (plated-through holes) extending through the second dielectric board. A lamination process may be used to fuse together the first and second dielectric boards **63**, **66** to form a multi-layer board assembly. In some implementations, another layer of dielectric board material **68** may be laminated over the top of the radiating element **42** to serve as the radome **62**.

As described previously, the conductive cavity **52** within which the radiating element **42** and the PDEBG structure **44** are housed may consist of a recess within a conductive surface associated with a mounting platform (e.g., a vehicle, etc.). In some embodiments, however, the walls **54** and the floor **58** of the cavity **52** may be deposited or otherwise formed about the other elements of the antenna **40** before mounting. The resulting assembly, with the cavity walls already formed, may then be mounted to a mounting surface. Other techniques for forming the antenna structures of FIGS. **1**, **2**, and **3** may alternatively be used as long as the dimensions, geometries, and structures are maintained. These other techniques may include, for example, additive manufacturing (e.g., 3D printing), direct energy deposition, 3D lamination, and/or others.

With reference to FIG. **3**, to achieve enhanced performance characteristics, the radiating element **42**, the PDEBG structure **44**, and the conductive cavity **52** are designed together. Traditionally, it has been considered a detriment to mount an antenna within a cavity. That is, the overall performance of the resulting antenna was invariably thought to be worse than the performance of the same antenna without a cavity. It has been found, however, that careful design of all elements together can result in an antenna within a cavity that has performance characteristics that exceed those of a similar antenna without a cavity. In some cases, an antenna can be achieved that performs like a much larger antenna, but within a smaller, more compact package. As will be described in greater detail, the design must take into account the effects that the cavity may have on the operation of other components of the antenna. This may include, for example, performance effects caused by capacitances between the walls **54** of the cavity **52** and the unit cells **46** of the EBG structure **44**. In some embodiments, this may also include performance effects of capacitances between the walls **54** of the cavity **52** and the radiating element **42**. In at least one implementation, the cavity **52** is used as an additional design variable to tune the antenna **40** for broadband operation. It was found that careful design of cavity size, along with proper placement of structures within the cavity, can permit an additional resonance to be achieved that can be used to broaden the operational bandwidth of the antenna for circularly polarized operation.

FIG. **4** is a flowchart illustrating an exemplary method for designing an antenna in accordance with an embodiment. As shown, an approximate size of the conductive cavity of the antenna may first be determined (block **82**). This approximate size may be dictated by, for example, the intended deployment location of the antenna or some other system requirement. Next, a number and arrangement of unit cells to use in the PDEBG structure may be selected (block **84**). A dielectric material may also be selected that will allow this arrangement of unit cells to fit within the approximate cavity size (block **66**). At some point, a radiating element may be selected to achieve desired horizontal and vertical field magnitudes for the antenna (e.g., equal field magnitudes to achieve circular polarization) (block **88**). The type of radiating element, as well as the size, shape, and orientation of the element, may be selected. The design of the individual unit cells may next be undertaken (block **90**). Modeling may be done to determine the correct phase response of the PDEBG structure to produce a 90 degree phase shift between total horizontal and vertical electric field components for the antenna. During this stage, the modeling may take into account the presence of the cavity walls and changes can be made to, for example, the dielectric material, the size of the unit cell elements, the size of the cavity, and/or other parameters to find values that work together to achieve an enhanced circularly polarized bandwidth (block **92**). Although illustrated in a particular order in FIG. **4**, it should be understood that changes may be made to the order of the blocks in different implementations. In addition, it should be understood that two or more of the blocks may be implemented concurrently in various implementations. Computer design tools/software may be used to facilitate the modeling and design process in some embodiments (e.g., the Ansys HFSS™ 3D electromagnetic simulation tool, etc.).

In a typical EBG structure, there will be a capacitance between adjacent pairs of units cell elements. During the design process, the cavity may be thought of as providing additional capacitance (e.g., capacitance between the walls of the cavity and the outermost unit cells of the EBG structure) that can be used as a degree of freedom in the design. This capacitance may be adjusted by, for example, changing the distance between the cavity walls **54** and the outermost unit cells of the EBG structure. It was found that by appropriately selecting this capacitance, the EBG structure **44** could be made to appear as though it had an image of additional rows and columns of unit cells. By making the

EBG structures appear larger, the effective aperture appears larger and enhanced circularly polarized bandwidth can be achieved in the antenna. Properly selected, this additional capacitance can produce an additional resonance in the design that serves to increase the bandwidth over which circularly polarized operation is possible.

If the width of the cavity is adjusted with respect to the EBG, the side capacitance will change and this will impact the second resonance right hand response of the antenna. Similarly, if the length of the cavity is adjusted with respect to the EBG, the corresponding capacitance will change and this will impact the second resonance left hand response of the antenna. If both the length and the width of the cavity are tuned together and tuned with the other antenna parameters, a second resonance may be achieved to produce an overall wideband response.

FIG. **5** is a plot illustrating an input impedance response (S**11**) of an exemplary antenna design in accordance with an embodiment. The plot includes both a simulated response curve and measured prototype response curves for the antenna design. As shown, the measured results agree well with the simulation. A wide impedance bandwidth of approximately 20.72 percent is achieved in the antenna. This impedance bandwidth is adequate for most modern data link systems. As shown in the FIG. **5**, this impedance bandwidth is significantly larger than the bandwidth **100** achieved in a prior EM coupled, circularly polarized antenna design. A second resonance is achieved at about 4.25 GHz by designing the cavity, the PDEBG structure, and the radiating element to work together.

FIG. **6** is a plot showing antenna gain at zenith for right hand circular polarization (RHCP) operation versus frequency for the exemplary antenna design. Again, both simulated and measured results are shown. The plot shows that a peak RH gain of approximately 8.98 dB was achieved by the design. The 6 dB bandwidth of the gain response of FIG. **6** is significantly larger than the bandwidth **102** of the prior EM coupled, circularly polarized antenna design. FIG. **7** is a plot showing the axial ratio (AR) at zenith versus frequency for the exemplary antenna design. Simulated and measured results are shown. The plot of FIG. **7** shows that a 6 dB AR bandwidth of approximately 19.08 percent was achieved by the design. This translates to a 6 dB AR angular coverage of +/−60°. Similarly, a 3 dB AR bandwidth of 15.58 percent was achieved. These AR bandwidths are significantly larger than those of the prior EM coupled, circularly polarized antenna design. This translates to a 3 dB AR angular coverage of +/−40°.

FIG. **8** is a plot showing gain versus azimuth angle for right hand circular polarization (RHCP) operation for the exemplary antenna design. FIG. **9** is a plot showing axial ratio versus azimuth angle for the exemplary antenna design. Both simulated and measured results are shown. In each of these plots, the measured results closely match the simulations. FIG. **10** is a table comparing the operational parameters of the exemplary antenna design to those of the prior EM coupled, circularly polarized antenna design.

In some embodiments, multiple polarization dependent electromagnetic band gap (PDBG) antennas are implemented together as an array antenna. FIG. **11** is a diagram illustrating an exemplary array antenna **110** in accordance with an embodiment. As shown, array antenna **110** includes a number of antenna assemblies (e.g., antenna assembly **10** of FIG. **1**, etc.) installed within corresponding cavities of as mounting surface **112**. As described previously, in some embodiments, the mounting surface **112** may be the exterior skin of a vehicle or other mounting platform. The antenna

assemblies **10** may be flush mounted within the various cavities to reduce problems related to, for example, wind drag. In some embodiments, however, flush mounting is not used. One or more beamformers may be coupled to the various antenna assemblies for use in forming beams using the various antenna elements. Because each of the elements of the array antenna **110** are housed within cavities, cross talk between the elements will typically be lower than it would be without cavities.

FIG. **12** is a projection view illustrating an exemplary antenna assembly **120** in accordance with another embodiment. The antenna assembly **120** of FIG. **12** is similar to the antenna assembly **10** of FIG. **1**, except an additional radiating element **122** has been added above the PDEBG structure **14**. An additional feed **124** is also provided to feed the additional radiating element **122**. The feed **124** may include a coaxial feed that extends through the PDEBG structure **14** and the ground plane **16** from below or some other type of feed structure. The additional radiating element **122** may be oriented in a direction that is orthogonal to the orientation of the first radiating element **12**. Further, the additional radiating element **122** may be located on a different metal layer of the antenna assembly **120** than the first radiating element **12** (e.g., a higher layer, etc.). In some implementations, one or more dielectric radome layers may be mounted above the uppermost radiating element (e.g., above radiating element **122** in FIG. **12**).

The antenna assembly **120** may be mounted within a cavity as described previously (e.g., cavity **32** of FIG. **2**, etc) to form a completed antenna. In addition, the antenna assembly **120** and the cavity in which it is mounted may be designed together to achieve enhanced rotational polarization performance (e.g., circularly polarized bandwidth, etc.). As described previously, in some implementations, this may involve adjusting dimensions of the cavity **52** as an additional design variable to tune the overall antenna for broadband operation. In some embodiments, a number of antenna assemblies **120** may be mounted within an array of cavities to form an antenna array (similar to, for example, array **110** of FIG. **11**).

As described previously, the first radiating element **12** may be oriented at a non-zero angle with respect to the units cells **24** of the PDEBG structure **14** to facilitate operation with circularly-polarized or elliptically polarized signals. Similarly, the second radiating element **122** may be oriented at a non-zero angle with respect to the units cells **24** of the PDEBG structure **14** to facilitate operation with circularly-polarized or elliptically polarized signals. In addition, as described above, the first and second radiating elements **12**, **122** may be oriented in orthogonal directions to one another. The antenna **30** of FIG. **2** is capable of achieving either left hand rotational polarization or right hand rotational polarization. An antenna using the antenna assembly **120** of FIG. **12** within a cavity can achieve any combination of left hand operation, right hand operation, or elliptical operation by switching between the feeds or simultaneously exiting both feed elements. In addition, this can all be done with the increased performance provided by the tuned cavity capacitance.

The techniques and structures described herein may be used, in some implementations, to generate conformal antennas or antenna arrays that conform to a curved surface on the exterior of a mounting platform (e.g., a missile, an aircraft, etc.). When used in conformal applications, the structures described above can be re-optimized for a conformal cavity. Techniques for adapting an antenna design for use in a conformal application are well known in the art and typically include re-tuning the antenna parameters for the conformal surface.

The antenna designs and design techniques described herein have application in a wide variety of different applications. For example, the antennas may be used as active or passive antenna elements for missile sensors that require wide circular polarization bandwidth, higher CP gain to support link margin, and wide impedance bandwidth to support higher data-rates, within a small volume. They may also be used as antennas for land-based, sea-based, or satellite communications. Because antennas having small antenna volume are possible, the antennas are well suited for use on small missile airframes. The antennas may also be used in, for example, handheld communication devices (e.g., cell phones, smart phones, etc.), commercial aircraft communication systems, automobile-based communications systems (e.g., personal communications, traffic updates, emergency response communication, collision avoidance systems, etc.), Satellite Digital Audio Radio Service (SDARS) communications, proximity readers and other RFID structures, radar systems, global positioning system (GPS) communications, and/or others. In at least one embodiment, the antenna designs are adapted for use in medical imaging systems. The antenna designs described herein may be used for both transmit and receive operations. Many other applications are also possible.

As used herein, the phrases "circularly polarized," "circular polarization," and the like are not intended to imply perfect circular polarization but, instead, may refer to situations where a relatively low axial ratio is achieved. Thus, phrases such as "a high circularly polarized bandwidth" and the like are used to refer to scenarios where a relatively low axial ratio is maintained over a relatively large frequency range. Such phrases are not meant to be limited to situations where perfect circular polarization (i.e., axial ratio equals 1) is achieved over an extended bandwidth. In some embodiments, an antenna may be provided that is configured to achieve elliptically polarized operation (non-circular). In these embodiments, parameters such as the angle of the rotated radiating element (e.g., the rotated patch element **12** of FIG. **1**), the reflected phase of the PDEBG structure, and others may be designed to achieve as desired level of elliptical polarization.

Having described exemplary embodiments of the invention, it will now become apparent to one of ordinary skill in the art that other embodiments incorporating their concepts may also be used. The embodiments contained herein should not be limited to disclosed embodiments but rather should be limited only by the spirit and scope of the appended claims. All publications and references cited herein are expressly incorporated herein by reference in their entirety.

What is claimed is:

1. A rotationally polarized antenna comprising:

a ground plane;

a polarization dependent electromagnetic band gap (PDEBG) structure disposed above the ground plane, the PDEBG structure having a number of unit cells arranged in rows and columns;

an orientable radiating element disposed above the PDEBG structure, the orientable radiating element having a long dimension and a short dimension; and

a conductive cavity encompassing the PDEBG structure and the orientable radiating element, the conductive cavity being open on a radiating side of the antenna, wherein a distance between side walls of the conductive cavity and one or more outermost edges of the PDEBG structure produces an additional resonance in an electrical response of the antenna, the distance selected to increase (i) an effective aperture of the antenna and (ii) a bandwidth of the antenna, in relation to the effective aperture and bandwidth without the additional resonance;

wherein the orientable radiating element is oriented at a non-zero angle with respect to the rows and columns of the PDEBG structure, the angle selected such that the orientable radiating element supports one of: (i) substantially equal horizontal and vertical electric field magnitudes for use with circularly polarized waves, and (ii) different horizontal and vertical electric field magnitudes for use with non-circular elliptically polarized waves.

2. The antenna of claim **1**, wherein:

the antenna is configured for use with circularly polarized waves.

3. The antenna of claim **1**, wherein:

the PDEBG structure, the orientable radiating element, and the conductive cavity are configured together to achieve an enhanced operational bandwidth.

4. The antenna of claim **1**, wherein:

the orientable radiating element includes one of: a patch element, a dipole element, and a monopole element.

5. The antenna of claim **1**, further comprising:

a feed coupled to the orientable radiating element through the ground plane and the PDEBG structure.

6. The antenna of claim **1**, wherein:

the conductive cavity has a floor that serves as the ground plane of the antenna.

7. The antenna of claim **1**, further comprising:

a radome layer covering an upper surface of the orientable radiating element.

8. The antenna of claim **7**, wherein:

an upper surface of the radome layer is substantially flush with an upper edge of the conductive cavity.

9. The antenna of claim **1**, wherein:

an upper surface of the orientable radiating element is substantially flush with an upper edge of the conductive cavity.

10. The antenna of claim **1**, wherein:

the conductive cavity is formed within an outer skin of a vehicle; and

an upper surface of the antenna is flush with the outer skin of the vehicle.

11. The antenna of claim **10**, wherein:

the vehicle includes one of: a ground vehicle, a watercraft, an aircraft, and a spacecraft.

12. The antenna of claim **1**, wherein:

a length, a width, and a height of the conductive cavity are each less than a wavelength at the center frequency of the antenna.

13. The antenna of claim **1**, wherein:

the antenna is conformal to a curved surface of a mounting platform.

14. The antenna of claim **1**, wherein:

the orientable radiating element is a first orientable radiating element; and

the antenna further comprises a second orientable radiating element disposed above the PDEBG structure, the second orientable radiating element having a long dimension and a short dimension, the second orientable radiating element having an orientation that is orthogonal to an orientation of the first orientable radiating element, wherein the second orientable radiating element is on a different metal layer than the first orientable radiating element.

15. The rotationally polarized antenna of claim **1**, wherein the distance is selected by adjusting at least one of a length and a width of the conductive cavity relative to the PDEBG structure.

16. An antenna assembly for use in forming a rotationally polarized antenna, comprising:

a polarization dependent electromagnetic band gap (PDEBG) structure having a plurality of unit cells arranged in rows and columns; and

an orientable radiating element disposed above the PDEBG structure, the orientable radiating element having a long dimension and a short dimension, the orientable radiating element being held in a fixed position with respect to the PDEBG structure so that the long dimension of the orientable radiating element forms a non-zero angle with both the rows and columns of the PDEBG structure, the non-zero angle selected such that the orientable radiating element supports one of: (i) substantially equal horizontal and vertical electric field magnitudes for use with circularly polarized waves, and (ii) different horizontal and vertical electric field magnitudes for use with non-circular elliptically polarized waves;

wherein the antenna assembly is configured for insertion into a conductive cavity having dimensions that are selected to form an antenna having radiation performance that is characteristic of a larger antenna, wherein a distance between side walls of the conductive cavity and one or more outermost edges of the PDEBG structure produces an additional resonance in an electrical response of the antenna, the distance selected to increase (i) an effective aperture of the antenna and (ii) a bandwidth of the antenna, in relation to the effective aperture and bandwidth without the additional resonance.

17. The antenna assembly of claim **16**, wherein:

the PDEBG structure and the orientable radiating element are formed on printed circuit boards.

18. The antenna assembly of claim **16**, further comprising:

a ground plane on an opposite side of the PDEBG structure from the orientable radiating element, the ground plane to contact a floor of the conductive cavity when the antenna assembly is installed therein.

19. The antenna assembly of claim **16**, further comprising:

a feed coupled to the orientable radiating element through the PDEBG structure.

20. The antenna assembly of claim **16**, wherein:

the orientable radiating element is a patch element.

21. The antenna assembly of claim **16**, wherein:

the orientable radiating element is one of: a dipole element and a monopole element.

22. The antenna assembly of claim **16**, wherein:

the antenna assembly is configured for insertion into a conductive cavity within an outer skin of a vehicle; and

the antenna assembly has a height that allows the antenna assembly to be mounted in the conductive cavity substantially flush to the outer skin of the vehicle.

23. The antenna assembly of claim **16**, wherein:

the orientable radiating element is a first orientable radiating element; and

the antenna assembly further comprises a second orientable radiating element disposed above the PDEBG structure, the second orientable radiating element having a long dimension and a short dimension, the second orientable radiating element having an orientation that is orthogonal to an orientation of the first orientable radiating element, wherein the second orientable radiating element is on a different metal layer than the first orientable radiating element.

24. The antenna assembly of claim **16**, wherein the distance is selected by adjusting at least one of a length and a width of the conductive cavity relative to the PDEBG structure.

25. A method for designing a rotationally polarized antenna having at least one orientable radiating element disposed above a polarization-dependent electromagnetic band gap (PDEBG) structure within a conductive cavity, the at least one orientable radiating element being oriented at a non-zero angle with respect to the PDEBG structure, the method comprising:

determining an approximate size of the conductive cavity;

selecting a dielectric material and a number and arrangement of unit cells to use in the PDEBG structure that will fit within the approximate size of the conductive cavity;

selecting an orientable radiating element;

selecting the non-zero angle such that the selected orientable radiating element supports one of: (i) substantially equal horizontal and vertical electric field magnitudes for use with circularly polarized waves, and (ii) different horizontal and vertical electric field magnitudes for use with non-circular elliptically polarized waves;

designing a unit cell of the PDEBG structure that will result in a 90 degree phase shift between total horizontal and vertical electric field components of the antenna, wherein designing a unit cell takes into consideration performance effects of the conductive cavity on the operation of the PDEBG structure; and

adjusting a size of at least the conductive cavity to achieve an enhanced bandwidth for the rotationally polarized antenna, wherein a distance between side walls of the conductive cavity and one or more outermost edges of the PDEBG structure produces an additional resonance in an electrical response of the antenna, the distance selected to increase (i) an effective aperture of the antenna and (ii) a bandwidth of the antenna, in relation to the effective aperture and bandwidth without the additional resonance.

26. The method of claim **25**, wherein:

designing a unit cell of the PDEBG structure includes using electromagnetic simulation software.

27. The method of claim **25**, wherein:

designing a unit cell of the PDEBG structure includes modeling a capacitance between walls of the conductive cavity and edges of the PDEBG structure.

28. The method of claim **25**, further comprising:

selecting a second orientable radiating element to be mounted above the PDEBG structure and the first orientable radiating element, the second orientable radiating element to be oriented in a direction that is orthogonal to an orientation direction of the first orientable radiating element.

29. The method of claim **25**, wherein adjusting the size of at least the conductive cavity comprises adjusting at least one of a length and a width of the conductive cavity relative to the PDEBG structure.

* * * * *